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The stability of flame holders.

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THE STABILITY OF FLAME HOLDERS
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May 1948   Troy, N. Y.

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BY

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Submitted to the faculty of the Rensselaer Polytechnic

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the degree of Master of Science.

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THE STABILITY OF FLAME HOLDERS

INTRODUCTION

A flame holder is a device placed in a stream of rapidly flowing combustible mixture to anchor the flame and to make burning possible. The flame holder has its most immediate application in the ram jet field, where counter flows are impractical, and it is desirable that combustion take place at as high a stream velocity as possible. The desired stream velocities far exceed the flame propagation velocities; thus, the flame holder is introduced into the stream to prevent the blowing out of the flame from the combustion region and to anchor the flame at a predetermined point.

To date no satisfactory theory exists in the published literature as to the mechanism by which the flame holder accomplishes its mission, and most of the progress that has been made thus far has been made by trial experiment in the laboratory. There is, however, one detail in which all flame holders, no matter how complicated they may appear, are similar. They have built into them an exit area to approach area ratio.

The purpose of this paper is to attack the problem of flame holder stability as a flow problem from an area ratio point of view in an effort to establish the stable region of operation for a flame holder. This field of stable operation derived on a flow basis will be valid only as long as the requisites for combustion are met.

Most of the studies in burning streams have been made on flame propagation.[1]* The main purpose is to relate the velocity of the flame front relative to the unburnt gas to the fundamental physical and chemical properties of the combustible mixture. Although the first attempts to solve this problem were made as long ago as fifty years, the problem is still not solved, and what has been accomplished is of little value as far as practical application is concerned.

The main reason for the failure of solution of the flame propagation problem became apparent when research of combustion reactions revealed the extremely complicated nature of the ordinary combustion process. It is now common knowledge to those working in the field of combustion research that combustion reactions take place by long, complicated reaction chains involving unstable intermediate products.[2]* Complete knowledge of the details of these reaction chains has not yet been compiled, but the basis of the theory appears very sound and has been completely worked out for some of the simpler reactions. The present chemical

representation of combustion equations merely represents a hypothetical combustion mechanism. These equations indicate the initial and end products, but they do not reveal the complicated path of the actual combustion process which controls the rate of energy release from the fuel and, consequently, the efficiency of burning.

To include the effects of heat conduction, diffusion, and chemical kinetics, modified by complicated flow conditions in a theory for flame holders, is completely out of the question at the present time both from the mathematical complication involved and the fact that the details of the chemical kinetics are not fully understood. The idea of this paper is to treat the combustion process in a flame holder as a flow phenomena, with the complicated mechanism of combustion present at all times, in an attempt to predict the region of stable operation of a flame holder of given area ratio.

THEORETICAL DEVELOPMENT

As stated before, the objective of the investigation was
to find a basis for which the temperature range of stable
operation could be estimated from the area ratio of a flame
holder. Although it has been previously pointed out that the
mechanism of combustion is very complicated, in the following
development the mechanism is assumed to exist.
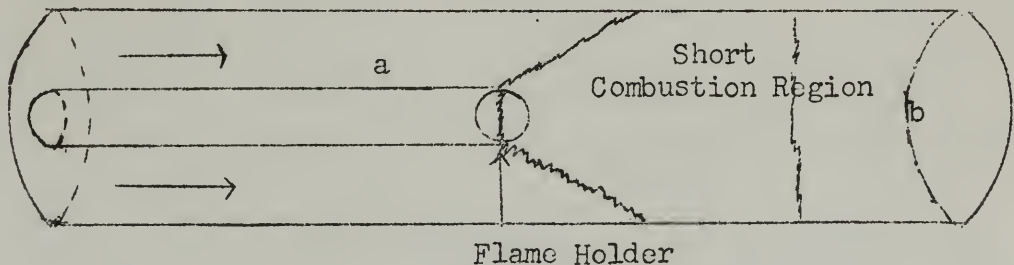
Flame Holder

Figure A

Assumptions:

1. Short combustion region with negligible capacity
   to store gases.

2. Flow at approach to flame holder, state (a), is
   pressure sensitive only.

3. Flow at the exit of the combustion region, state
   (b), is both temperature and pressure sensitive.

4. The combustion process, stabilized by the flame
   holder is independent of flow conditions and is
   present at all times.

Expressing the assumptions mathematically we have,

From assumption 1: $W_a = W_b$ . . . . (1)

From assumption 2: $W_a = f(P)$ . . . . , (2)

From assumption 3: $W_b = f(P, T)$ . . . . (3)

Differentiating (2) and (3):

$$dW_a = \frac{dW_a}{dP} \, dP \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \text{(4)}$$

$$dW_b = \frac{\delta W_b}{\delta P} \, dP + \frac{\delta W_b}{\delta T} \, dT \quad \ldots \ldots \ldots \ldots \ldots \text{(5)}$$

If we expand to finite increments about some stable point of operation, state o, defined by W_o, P_o, and T_o, equations (3) and (4) become,

$$W_a - W_o = \frac{dW_a}{dP} \, (P - P_o) \quad \ldots \ldots \ldots \ldots \ldots \text{(6)}$$

$$W_b - W_o = \frac{\delta W_b}{\delta P} \, (P - P_o) + \frac{\delta W_b}{\delta T} \, (T - T_o) \quad \ldots \text{(7)}$$

If fuel remains constant considering constant specific heats,

$$W_o (T_o - T_a) = W_a (T - T_a), \text{ or}$$

$$T = T_a + \frac{W_o}{W_a} (T_o - T_a) \quad \ldots \ldots \ldots \ldots \ldots \text{(8)}$$

Subtracting T_o from both sides of equation (8),

$$T - T_o = -(T_o - T_a)(1 - \frac{W_o}{W_a}) = -\frac{(W_a - W_o)}{W_a}(T_o - T_a)$$

But $\dfrac{W_a - W_o}{W_a} \iint \dfrac{W_a - W_o}{W_o}$

$$T - T_o \ \ // \!\!\!\!- (T_o - T_a) \ \dfrac{(W_a - W_o)}{W_o} \ \ldots \ldots \ldots \ (9)$$

Substituting (9) in (7),

$$W_b - W_o = \dfrac{\varepsilon W_b}{\delta P} \ (P - P_o) - \dfrac{\delta W_b}{\delta T} \ \dfrac{(W_a - W_o)}{W_o} \ (T_o - T_a) \ \ldots \ (10)$$

But from (6) $W_a - W_o = \dfrac{dW_a}{dP} \ (P - P_o)$

Substituting (6) in (10),

$$W_b - W_o = \dfrac{\varepsilon W_b}{\delta P} \ (P - P_o) - \dfrac{\delta W_b}{\delta T} \ \dfrac{dW_a}{dP} \ (P - P_o) \ \dfrac{(T_o - T_a)}{W_o}$$

or,

$$\dfrac{W_b - W_o}{P - P_o} = \dfrac{\varepsilon W_b}{\delta P} - \dfrac{(T_o - T_a)}{W_o} \ \dfrac{\varepsilon W_b}{\delta T} \ \dfrac{dW_a}{dP} \ \ldots \ldots \ (11)$$

The moment there is a pressure disturbance in the combustion region, a velocity is propagated counter flow due to the pressure disturbance.[4]* The effect can be expressed mathematically as follows:

$$dP = - \ dV \sqrt{E \rho} \qquad \text{where E is bulk modulus}$$
$$E = \gamma P_o$$

or,

$$dV = - \ \dfrac{(P - P_o)}{\sqrt{E \rho}} \ \ldots \ldots \ldots \ldots \ldots \ldots \ (12)$$

But $\qquad W = \rho A V g$

Assuming constant density,

$$dW_a = \rho\, Ag\, dV = -\rho Ag\, \frac{(P - P_0)}{\sqrt{\gamma P_0\, \rho}}$$

But

$$P_0\, P_a \,//\, P_a^2 \quad \text{and} \quad \frac{W_a - W_0}{P - P_0} \,//\, \frac{dW_a}{dP}$$

$$\frac{W_a - W_0}{P - P_0} \,//\, \frac{dW_a}{dP} \,//\, -Ag \sqrt{\frac{T_a}{\gamma gR}\, \frac{1}{T_a}}$$

or,

$$\frac{P_0\, dW_a}{W_0\, dP} = \frac{-\sqrt{\dfrac{g}{\gamma R}}}{\dfrac{W_0}{A_a}\, \dfrac{\sqrt{T_a}}{P_0}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (13)$$

Similarly, the pressure disturbance causes a velocity to be propagated with the flow.

$$dWb = \rho_2\, Ag\, dV$$

Where $\quad dV = \dfrac{(P - P_0)}{\sqrt{EP_0}} \quad$ Where E is bulk modulus
$$E = \gamma P_0$$

Analogous to the derivation for counter flow disturbance,

$$\frac{P_0}{W_0}\, \frac{dWb}{dP} = \frac{\sqrt{\dfrac{g}{\gamma R}}}{\dfrac{W_0}{Ab}\, \dfrac{\sqrt{T_0}}{P_0}} \quad \ldots\ldots\ldots\ldots\ldots\ldots (14)$$

Since,

$$W = \rho\, AgV = \frac{P}{RT}\, AV$$

Taking logarithms and differentiating,

$$\frac{\delta W}{W} = - \frac{\delta T}{T} \quad \text{or} \quad \frac{T}{W} \frac{\delta W}{\delta T} = -1$$

But,

$$\frac{T}{W} \frac{\delta W}{\delta T} = -1 \bigg/ \bigg/ \frac{T_o}{W_o} \frac{\delta Wb}{\delta T} \quad \ldots \ldots \ldots \ldots \quad (15)$$

Multiplying and dividing (11) by $\frac{W_o}{P_o}$, and supplying in the

second term on the right a $\frac{T_o}{T_o}$, we have,

$$\frac{Wb - W_o}{P - P_o} = \left[\frac{P_o}{W_o} \frac{dWb}{dP} - \frac{(T_o - T_a)}{T_o} \frac{T_o}{W_o} \frac{\delta Wb}{\delta T} \frac{P_o}{W_o} \frac{dWa}{dP} \right] \frac{W_o}{P_o} \cdot (16)$$

Substituting (13), (14), and (15) in (16),

$$\frac{Wb - W_o}{P - P_o} = \left[\frac{\sqrt{\frac{g}{\gamma R}}}{\frac{W_o}{Ab} \frac{\sqrt{T_o}}{P_o}} - \frac{(T_o - T_a)}{T_o} \frac{\sqrt{\frac{g}{\gamma R}}}{\frac{W_o}{Aa} \frac{\sqrt{T_a}}{P_o}} \right] \frac{W_o}{P_o}$$

Setting $\frac{Wb - W_o}{P - P_o} = 0$ and solving for the area ratio,

$$\frac{Ab}{Aa} = \sqrt{\frac{T_o}{T_a}} \frac{(T_o - T_a)}{T_o} \quad \ldots \ldots \ldots \ldots \ldots \quad (17)$$

or,

$$\frac{Ab}{Aa} = \sqrt{\frac{T_o}{T_a}} - \frac{1}{\sqrt{\frac{T_o}{T_a}}} \quad \ldots \ldots \ldots \ldots \ldots \quad (18)$$

As can be seen from (18) the area ratio of a flame holder

can be expressed as a function of the temperature ratio with

certain simplifying assumptions and approximations.

Henceforth in this report when term area ratio of flame holder is used, it is implied the ratio of A_b/A_a or ratio of exit gas area to inlet gas area, and likewise temperature ratio is T_o/T_a or ratio of exit gas temperature to inlet gas temperature.

ANALYSIS OF PROBLEM

From the theoretical development one observes that the area ratio of a flame holder can be expressed as a function of the temperature ratio on the basis of certain approximations and assumptions. In deriving this simplified expression, the rate of change of exit weight flow from flame holder combustion region with respect to pressure in the flame holder combustion region was assumed to be zero, and the energy release of fuel was assumed to be independent of flow conditions.

A flame holder of the simplest possible construction would be built, and the area ratio of the flame holder varied by using various sizes of combustion tubes in order to verify the validity of the theoretically developed equation and to interpret its significance by experimental results.

A flame holder was constructed of standard 3/8-inch pipe with a flat plate welded over the end, the stabilizing area.

A small hole was drilled in the flat plate in order to install a pilot light for combustion initation. Various combustion tubes were mounted coaxially with the flame holder. A pre-mixed . gas system was selected in order to minimize mixing and gas diffusion problems. A high pressure or stiff fuel system was selected in order that fluctuations in air supply or pulsations in burner would not be reflected into the fuel supply. With the equipment selected, by holding variations in other variables to a minimum, and varying the area ratio of flame holder by using variable combustion tubes, the importance of area ratio and temperature ratio on stability would be carried out.

The investigation was carried out in the Heat Transfer Laboratory of the Mechanical Engineering Department, Rensselaer Polytechnic Institute, Troy, New York.

EQUIPMENT AND PROCEDURE

EQUIPMENT

Since the objective of the experiment was to find the
field of stable operation of flame holders from the standpoint
of flow conditions, the simplest apparatus was selected in order
to fulfill the requirements of the theoretical development.
The experimental apparatus is shown schematically in Fig.(B) and (C),
and in photographs 1 and 2. The essential parts of the apparatus
are the air supply and air meter, the fuel supply and fuel meter,
the mixing chamber, the flame holder, the pilot light, and the
combustion tubes. A detailed description of each of the essential
parts is as follows:

Air Supply and Air Meter: The air supply was taken
from the building supply which was furnished by an
Ingersoll-Rand Type 30 Compressor. The supply was
held constant by opening a bleed-off valve in order
to keep the compressor in continuous operation, and
controlling the flow to air meter with a throttle valve.
Air supply could be maintained within a .010 inch of
water across the air nozzle as measured by an inclined
draft gage. The air meter consisted of a standard
A.S.M.E. nozzle of .488 inches in diameter made of
aluminum. The nozzle was mounted in an aluminum

plate and connected by flanges to seven-inch
lengths of standard three-inch pipes, the approach
to and exit from the nozzle. The upstream wall
tap was one-half inch from the nozzle plate and the
downstream wall tap as one-eighth inch from the end
of the nozzle. A Weston type dial thermometer was
installed on the downstream side of the nozzle
plate for measurement of air temperature. The
approach and exit leads to the air meter were one-
quarter inch pipes coupled to the three-inch sections.
The pressure on the downstream side of the nozzle
was read in inches of mercury on a standard U-tube
gage, and the differential pressure across the nozzle
was measured on a one-inch inclined draft gage. The
nozzle coefficient of the air nozzle was assumed to
be unity. It is believed that the air flow measure-
ments were accurately determined to within two per
cent.

Fuel Supply and Fuel Meter: The fuel used was propane
sold under the trade name of "Pyrofax". The fuel was
in liquid form with vapor pressure supplying the
supply pressure. The vapor pressure of propane at
70° F. is about 107 lb./sq. in. gage, which gave a
more than adequate supply pressure. Some charac-
teristics of "Pyrofax" as furnished by the

supplier are as follows:

Heating Value   21,500 BTU/lb.

Ratio of Specific Heats   1.153

A pressure reducing valve was used to control the
pressure to the fuel meter. The amount of fuel
used was so small that the evaporation of the fuel
to a gaseous state did not lower the supply pressure
which remained constant throughout the experiment.
The temperature of the fuel was assumed to be that
of room temperature. The reducing valve was con-
nected to the fuel nozzle by means of rubber hose.
The fuel meter consisted of a 3/8-inch pipe approach
to a rounded nozzle, drilled with a number fifty
drill. The exit from the nozzle was 1/4-inch
standard pipe. The nozzle was made from a brass
1/4-inch pipe cap machined down to the above
specifications. The approach was well rounded, but
the straight section was slightly longer than that of
conventional nozzles. The fuel meter was placed
in series with the air meter for calibration. The
details of calibration using air as the medium are
shown in Appendix, Section A. The effective area
was calculated to be .00425 sq. in. In order to
calibrate the fuel meter with air meter as standard,

it was necessary to calibrate the fuel meter at flows far above the range at which the meter would be used, but it was decided to calibrate the meter in this way in order to have a standard that was in the system. The effective area .00425 sq. in. seems very reasonable allowing for any whip of the drill. A number sixty drill hole had also been used originally, but it was found to be too small and a larger number fifty drill hole was redrilled through it. It is considered that the fuel measurements were accurate to within five per cent.

Mixing Chamber: The mixing chamber consisted of fuel supply rod of 1/4-inch diameter stainless steel with a plugged end mounted concentrically along the axis of a 3/8-inch pipe T. The steel fuel tube was tapped by eight equally spaced number eighty drill holes, approximate diameter .0135 inches. The reason for using such small holes was to make a very stiff fuel system so that fluctuations in air supply or burner pulsations would not effect fuel supply. The fuel system did not vary with burner pulsation, but on increasing the pressure in the air system a cor-responding decrease in fuel supply would be noted which would be due to the decreased pressure drop across the fuel meter.

Flame Holder: The flame holder consisted of a 3/8-inch pipe with a flat plate welded over one end. The flame holder was mounted concentrically with the combustion tubes. The same flame holder was used throughout the experiment. The diameter of the flame holder was .683 inches.

Pilot Light: In order to initiate combustion the flame holder end was tapped with a small hole. The flame holder pipe was connected to the city gas system, and a flame of one-quarter to three-eighths inches high was used for ignition. When in operation, no change in the temperature of the exit gases from the combustion tube could be detected whether the pilot light was on or off.

Combustion Tubes: The combustion tubes were two feet long and of various internal diameters. The area ratio of the flame holder was varied by using a common area flame holder and varying the internal diameter of the combustion tubes. Tubes of pyrex glass, iron and porcelain were used for temperature traverse data. Combustion tubes for the stability test were as follows:

Composition	Internal Diameter – Inches	Area Ratio*
Tube 1, 50 mm pyrex	1.828	1.162
Tube 2, 1 1/4" iron pipe	1.365	1.330
Tube 3, 35 mm pyrex	1.250	1.425
Tube 4, 1" iron pipe	1.055	1.720

*Based on a common flame holder area of .683 in diameter.

It was considered desirable to use some pyrex tubes accompanied by slight plasticity and slight warpage in order that the combustion region could be observed without a complicated system of mirrors.

PROCEDURE

Pressure Measurement – All static pressures were measured on a U-tube manometer in inches of mercury. The differential pressure across the fuel meter and the air meter was measured on three- and one-inch inclined draft gage, respectively.

Flow Measurement – Section D, Appendix, outlines the method in which fuel and air flow calculations were made.

Temperature Measurement – The temperature was measured by means of a Chromel-Alumel thermocouple and a General Electric Type PJ-1-B4 Potentiometer. The conversion tables used were "Standard Conversion Tables for L. and N. Thermocouples", published by the Leeds and Northrup Company. Readings were reproducible throughout the experiment to within fifty degrees in the center of the combustion tube; however, wall readings were more erratic.

Temperature readings can be questioned on the basis
of (1) long exposure at high temperatures, (2) exposure to
burning in mixtures that might carburize or alter composition
of thermocouple wires, (3) radiation errors. The temperature
trends are of primary interest in this investigation, however.
It might be pointed out that where large gradients exist in
making a traverse, the readings to be observed close to the
wall are the most important readings since the flow area is
larger between successive radius increments. It was very
difficult with the equipment available to obtain very accurate
readings here where the temperature gradient was the greatest.
The temperatures in proximity of the wall unfortunately are
the most important in the experiment and are subject to the
greatest error.

Temperature Integration – There existed in all combustion
tubes a severe temperature gradient across the diameter of the
tube. Since in the theoretical development only mean tempera-
tures were used, some average temperature had to be evaluated.
An impact tube was placed in the combustion tube, and the
velocity traverse corresponded to the rough parabolic distribu-
tion of the temperature gradient.

Since $W = \rho A V g = \dfrac{PA}{R} \times \dfrac{V}{T}$, the static pressure
across the tube was constant. If the velocity and temperature
vary in the same manner across the combustion tube, then equal

areas in the tube have equal amounts of mass flux crossing them.
A temperature traverse was taken across the combustion tube and
plotted against the radius at various points. The combustion
tube area was then divided into six equal areas and the cor-
responding radii were plotted in on temperature traverse plots.
The temperatures of the equal area mid-points were averaged for
the mean temperature. The number six was selected because a
greater number of equal areas would have the effect of weighting
the temperatures near the wall more; however, the temperatures
near the wall are subject to the most error. Appendix, Section
B, shows a compilation of the temperature traverse data
calculated as outlined above. Fortunately, all the tubes tested
fell close to a general temperature curve, which fitted re-
markably well for all tubes at the flows tested. A general
curve was plotted in which the maximum temperature, or tempera-
ture at center of tube, was plotted against the average
temperature. All tubes were consistent with this curve.

Determination of Limits of Stable Burning — It was hoped
that some means other than audible observation could be used to
determine the stability limit. It was also suspected that
actual instability had set in before it was possible to hear
the burner pulsations. The exit gas temperature was plotted
against the square root of dHg across the fuel meter which is
proportional to the fuel input. Increasing the fuel causes a
rapid rise in temperature up to a certain point although in
the lower region the combustion is very rough owing to the very

After a certain point is reached a large increase in fuel is
required for a small increase in temperature of exit gases.
The points on either side of this point correspond roughly to
straight lines. By extrapolating these straight lines to
an intersection the lower limit of smooth burning was determined.
It is to be noted that the first audible pulsation occurs later
than the lower limit determined. The lower limit and the point
where pulsation is audible are the lower and upper limits of
smooth burning. The average temperature corresponding to the
temperature at the center was then taken from the temperature
calibration curve.
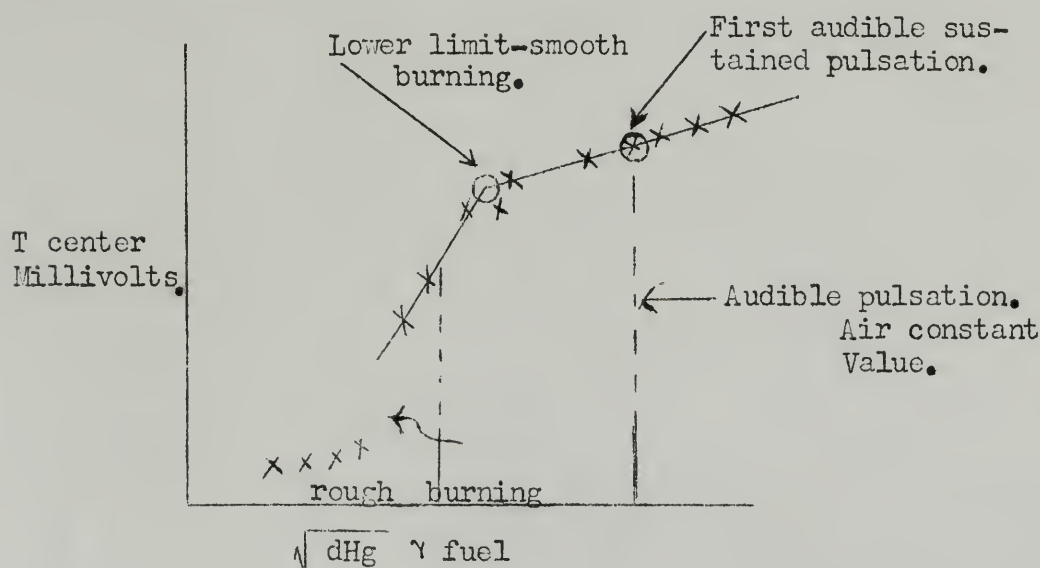
Figure D

RESULTS AND DISCUSSION

Before any analysis of stability could be attempted,
accurate measurement of air and fuel input together with the
temperature of the exit gases had to be made. Appendix A-1
shows the details of the fuel meter calibration. It was
thought that a temperature calibration curve for each combustion
tube would have to be made whereby the average or mean tempera-
ture could be read from the maximum temperature of the gases at
the center of the tube. Temperature traverses were taken
throughout the combustion region with various combustion tubes.

The actual combustion region was about one foot long ex-
tending from the flame holder down the tube to the exit. A
point 13 1/2" from the flame holder or   1/2" below the end of
the combustion tube was selected for the point at which all
traverses would be taken. Temperatures were observed to be
lower at the exit when longer, or two and one-half foot com-
bustion tubes were used.

Several runs were made on all types of combustion tubes.
The details of the combustion tube traverses with the mean
temperature evaluated as outlined previously in the procedure
are shown in the Appendix B. Fortunately, all the tubes tested
fell close to a general curve. Curve 3, Section G, Appendix,
shows the results of temperature traverses in plotted form.

The results of the stability test runs are shown in
Section C, Appendix. Since in most applications the air
supply will be relatively constant and temperature controlled
by varying the amount of fuel input, it was decided to conduct
the experiment in this manner. The air supply was set on a
constant value for the run, and the fuel input increased in
increments with the corresponding temperature at the center of
the tube recorded. The fuel was increased until continuous
sustained pulsation could be heard audibly. The fuel versus
temperature curve was plotted and the lower limit of stable
burning determined. Curve 2 shows a typical plot of average
data. The lower limit was determined as outlined before in
the procedure. No audible pulsation was observed on Tube
No. 1, 50 mm, pyrex, because flash-back occurred before pul-
sation indicating definitely that a pressure disturbance existed
in the combustion region. Pulsation occurred slightly later in
Tube No. 3, 30 mm, pyrex, and it is believed that this was due
to the fact that the tube was piped into the system by a rubber
connection which in effect shock-mounted the tube. With the
tube shock-mounted, the pulsation had to be of greater intensity
before it was noted. Table II-C shows a compilation of the
results of the stability tests. When the lower limit and
audible pulsation points were determined, the average tempera-
ture of the exit gases was obtained from the temperature
calibration curve, Curve 3.

After the mean temperatures of the exit gases at the
lower limit and the audible pulsation points were obtained,
the temperature ratios were computed and plotted on a dimension-
less plot as shown in Curve 1. Both the lower limit temperature
ratio and pulsation temperature ratios are shown plotted on the
curve together with the theoretically derived curve previously
developed.

Below the lower limit the combustion is rough because
the mixture is so lean that it will barely support combustion.
Above the audible pulsation point the combustion is obviously
unstable. These two points define the region of stable
burning. It is suspected that actual instability has begun
before it can be heard audibly, and that in the limit these
two points should coincide, giving a very narrow band of
stable operation.

From Curve 1, it is noted that the variation from the
theoretical curve is greater as the temperature ratio increases.
This increasing variation can be explained by the fact that no
radiation corrections were made to the thermocouple indicated
temperatures. If the true temperature is assumed to be on the
theoretical curve and the lower point of stability is used:

Radiation Correction $= k \, (T_t)^4$ T_t = Theoretical temp.
from curve.

Tube No. 4, 1" pipe, (largest area ratio), requires a radiation loss of 275 degrees for the lower limit point to be on the theoretical curve. Using this value as a basis to compute a common radiation constant, the following values were computed based on the average T_a equal to 69° F.

T_o/T_a (Predicated)= T_o/T_a from theoretical curve

corrected for radiation loss.

T_o/T_a (Observed)= T_o/T_a from data for lower limit

point.

Radiation Loss Degrees	T_o/T_a (Predicted)	T_o/T_a (Observed)	Error (%)
275° **	4.21	4.21	0
112°	3.58	3.29	8.1
89°	3.34	3.19	4.5
47°	2.94	2.90	1.36

**Values used to evaluate radiation constant for all tubes.

Thus, one can observe that by correcting for a radiation loss to bring one of the observed lower limit points to the theoretical curve the other points are brought into corresponding excellent agreement. These limits are well within the experimental error of the experiment. Also the radiation corrections are of the order of magnitude of those to be expected at the corresponding temperatures.

It might further be pointed out that the lower limit
of stability for a given area ratio for different values of
air flow occurs at the same air to fuel ratio which adds
consistency to the results.

The lower limit of stability represents the highest
economical temperature ratio of operation since increasing
the fuel input beyond this point does not give as great an
increase in exit gas temperature. On the other hand, it repre-
sents the lowest temperature ratio for stable burning.

The implications are that for a given air supply and
flame holder area ratio there is only one point of fuel input
for stable burning. Also that control of system by varying
fuel input is of little value since an increase or decrease
from the lower point of stability will throw the system unstable.

An Orsat analysis on exit gases was conducted on Tube No. 2,
1 1/4" pipe, in order to check the completeness of combustion
at the lower limit. Combustion was found to be complete, and
the air fuel ratios computed from the Orsat analysis agreed
favorably with the computations from air and fuel meters.
Section E, Appendix, shows results of the Orsat tests and the
calculations.

Table III-C, Appendix, shows the computed air to fuel ratios
for both the lower limit of stability point, and point where
first audible and continuous pulsation was observed.

Curve 4 is a plot of the mean results. It is interesting to
note that throughout the experiment the air to fuel ratios
were all greater than that corresponding to stoicheiometric
with the exception of one point.

CONCLUSIONS

Although no final conclusions can definitely be made on
the basis of this low flow experiment without further experi-
mentation, the implications are as follows:

(1) The region of stable operation of a flame holder
with uniflow, and homogenous mixture of combustible
gases is a narrow band on either side of the
equation defined by:

$$\frac{A_b}{A_a} = \sqrt{\frac{T_o}{T_a}} - \frac{1}{\sqrt{\frac{T_o}{T_a}}} \quad \ldots \ldots \ldots \ldots \quad (18)$$

Below the temperature ratio corresponding to that
defined by equation (18), rough burning is ex-
perienced because of the lean mixtures; above
this temperature ratio audible pulsation can be
heard. Pulsation is believed to start at the
lower limit or very soon thereafter, but is not
of sufficient intensity to be heard. In the limit
the lower limit of stable burning and the initial

pulsation point should approach the same point.

(2)   Control of temperature in a combustion tube

stabilized by a flame holder with uniflow,

homogenous mixture of combustible gases with

constant air supply by varying fuel input is

not practicable, since smooth burning occurs

very nearly at one point. Varying the fuel

input either side of this point throws the

system into instability.

APPENDIX

SECTION A

FUEL METER CALIBRATION

The fuel meter was calibrated with the standard A.S.M.E. .488-inch diameter nozzle. The coefficient of the standard nozzle was assumed to be one. The setup of the calibration was as follows:

T air = 71° F.

Bar = 29.92"Hg.

TABLE IA
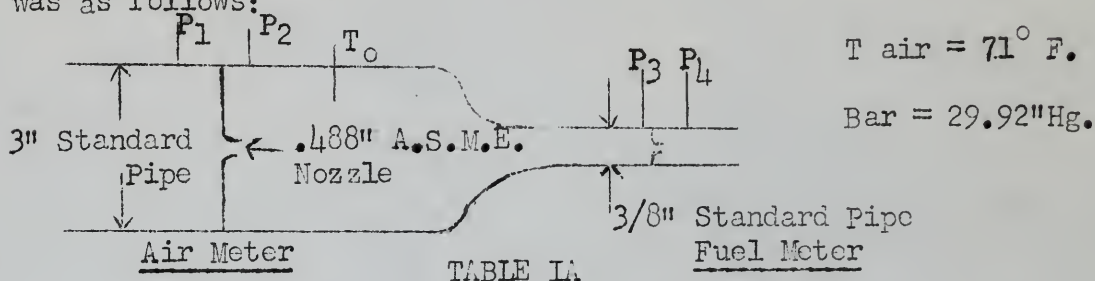
FUEL NOZZLE CALIBRATION DATA

Run	dH_1-2 in. H_2O	P_2 in. Hg. Gage	T_0 - - °F.	P_3 in. Hg. Gage	P_4 in. H_2O Gage
1	.016	2.41	66	2.41	2.2
2	.026	4.28	66	4.29	3.8
3	.036	6.55	66	6.56	5.70
4	.020	3.54	66	3.54	2.70
5	.060	13.45	68	13.35	10.70
6	.068	16.20	68	16.14	12.60
7	.050	10.40	68	10.40	8.3
8	.040	7.3	68	7.3	6.2
9	.030	5.3	68	5.3	4.5

*The differential head dH_1-2 was measured on a one-inch draft gage. The remaining readings were taken on standard U-tube manometers.

Sample calculation:

Since the Mach Number at point 2 is low,

$$\frac{P_1}{P_2} = \left[1 + \frac{\gamma-1}{2} \; M_2^2\right]^{\frac{\gamma}{\gamma-1}} = 1 + \frac{\gamma}{2} \; M_2^2$$

$$M_2 = \sqrt{\frac{2}{\gamma} \; \frac{dP}{P_2}} = \sqrt{\frac{d \; H_{1-2}}{P_2}} \; \sqrt{\frac{2}{\gamma} \times \frac{1}{13.6}} = .325 \sqrt{\frac{d \; H_{1-2}}{P_2}}$$

since,

$$\frac{W \sqrt{T_o}}{PA} = M \sqrt{\frac{\gamma g}{R} \left(1 + \frac{\gamma-1}{2} \; M^2\right)} = f \; (M) \quad (4)*$$

$$A_4 \text{ effective} = \frac{P_2}{P_4} \; \frac{f \; (M_2)}{f \; (M_4)} \; A_2$$

$$A_2 = 0.187 \text{ sq. in.}$$

M_4 was calculated using a reversible expansion from point 3 to point 4. Table II shows a summary of the calculations for A_4.

The mean effective area for the nine calibration runs was .00425 sq. in. The drill used to make the nozzle was a number 50 drill of approximately .00384 sq. in. area. The calculated effective area appears to be reasonable allowing for moderate drill whip.

TABLE II-A

SUMMARY OF CALCULATIONS FOR FUEL

NOZZLE CALIBRATION

Run	M_2	$f(M_2)*$	M_4	$f(M_4)*$	P_2'' Hg.	P_4'' Hg.	A_4 sq. in.
1	.00720	.00660	.327	.304	32.33	30.08	.00435
2	.00934	.00856	.435	.404	34.21	30.20	.00451
3	.01013	.00930	.520	.489	36.51	30.34	.00427
4	.00790	.00725	.399	.371	33.46	30.07	.00403
5	.01200	.01105	.720	.693	43.37	30.70	.00426
6	.01245	.01142	.780	.757	46.12	30.85	.00423
7	.01140	.01046	.645	.615	40.32	30.53	.00420
8	.01060	.00972	.567	.536	37.22	30.38	.00416
9	.00945	.00868	.474	.448	35.22	30.26	.00421

$$A_4 \text{ (Effective)} = C_1 A_4 \text{ (Actual)} = \frac{\sum\limits_{n=1}^{n=9} A_n}{9} = .00425 \text{ sq. in.}$$

$$* \ f(M) = M \sqrt{\frac{\gamma g}{R}\left(1 + \frac{\gamma-1}{2} M^2\right)}$$

SECTION B

TABLE I-B

TEMPERATURE TRAVERSE DATA

Temperatures in Millivolts.
X = distance in inches from center of
tube to where temperature was taken.

X In.	Run 1 50 mm	Run 2 50 mm	Run 3 50 mm	Run 4 35 mm	Run 5 35 mm
3/4	24.5	23.5	27.5	---	—
5/8	31.0	29.5	32.6	—	---
1/2	34.0	32.0	35.8	25.8	30.5
3/8	35.3	34.2	37.5	35.7	38.7
1/4	36.3	35.2	38.5	40.0	42.1
1/8	37.0	36.0	38.7	42.0	43.5
0	37.0	36.2	38.8	42.3	44.1
1/8	37.0	36.0	38.7	41.9	43.6
1/4	36.5	35.6	38.5	40.0	41.6
3/8	35.2	34.2	37.5	35.9	37.6
1/2	33.5	32.7	35.5	29.5	29.5
5/8	30.5	28.8	31.8	--	---
3/4	24.5	23.0	25.5	—	--

TABLE I-B (continued)

X In.	Run 6 35 mm	Run 7 30 mm	Run 8 30 mm	Run 9 30 mm	Run 10 Porcelain
1/2	30.8	28.0	33.0	37.0	--
3/8	37.7	32.0	35.5	37.0	35.0
1/4	42.0	39.5	40.5	42.0	44.7
1/8	44.1	42.7	44.2	45.4	46.5
0	44.5	43.9	45.7	46.0	47.0
1/8	44.5	43.5	--	--	--
1/4	43.2	40.5	--	--	--
3/8	39.0	33.5	--	--	--
1/2	30.8	--	--	--	--

X In.	Run 11 Por.	Run 12 Por.	Run 13 1" Pipe	Run 14 1" Pipe	Run 15 1" Pipe
Wall	40.0	41.2	23.6	26.0	26.5
3/8	--	--	31.2	35.0	36.7
1/4	45.6	46.5	39.5	41.0	42.1
1/8	48.4	49.5	42.4	43.8	45.0
0	48.6	50.0	43.6	45.1	47.0
1/8	--	--	41.5	44.8	46.1
1/4	--	--	37.8	40.8	41.8
3/8	--	--	30.5	31.0	31.8
Wall	--	--	24.8	27.5	28.1

TABLE I-B (continued)

X In.	Run 16 1 1/4" Pipe	Run 17 1 1/4" Pipe	Run 18 1 1/4" Pipe	Run 19 35 mm	Run 20 30 mm
Wall	20.0	21.8	23.2	---	---
1/2	27.8	29.5	29.1	24.0	---
3/8	32.5	34.2	30.6	30.0	24.5
1/4	35.8	37.8	38.9	33.8	29.5
1/8	37.5	39.5	41.0	36.7	34.5
0	39.0	40.5	41.8	37.4	35.5
1/8	38.7	40.5	41.1	36.0	---
1/4	37.5	39.8	40.2	33.2	---
3/8	34.6	37.5	38.3	30.0	---
1/2	28.0	32.0	32.1	24.6	---
Wall	21.0	22.2	23.5	---	---

X In.	Run 21 30 mm	Run 22 35 mm	Run 23 25 mm	Run 24 30 mm	Run 25 25 mm	Run 26 50 mm
3/4	---	---	---	---	---	17.2
5/8	---	---	---	---	---	20.5
1/2	---	20.2	---	---	---	22.8
3/8	20.0	25.0	18.0	15.5	20.0	24.0
1/4	25.0	27.2	20.3	19.4	21.0	24.8
1/8	30.0	29.5	26.2	21.8	29.2	25.0
0	31.2	30.5	28.3	22.8	33.8	25.2
1/8	30.9	29.0	27.4	21.4	30.5	---
1/4	28.0	27.2	23.1	18.0	---	---
3/8	21.5	24.1	18.8	14.2	---	---
1/2	---	20.5	---	---	---	---

TABLE II-B

SUMMARY OF TEMPERATURE TRAVERSE DATA

FOR TEMPERATURE CALIBRATION CURVE

Run	Tube	T Maximum °F.	T Average °F.
1	50 mm glass	1635	1263
2	50 mm glass	1600	1226
3	50 mm glass	1715	1384
4	35 mm glass	1880	1405
5	35 mm glass	1965	1502
6	35 mm glass	1990	1542
7	30 mm glass	1955	1546
8	30 mm glass	2040	1626
9	30 mm glass	2055	1693
10	1" Porcelain	2100	1795
11	1" Porcelain	2180	1889
12	1" Porcelain	2250	1983
13	1 1/4" steel pipe	1915	1461
14	1 1/4" steel pipe	2010	1511
15	1 1/4" steel pipe	2095	1573
16	1" steel pipe	1725	1288
17	1" steel pipe	1795	1374
18	1" steel pipe	1835	1434
19	35 mm glass	1640	1100
20	30 mm glass	1570	1100
21	30 mm glass	1380	940
22	35 mm glass	1350	935
23	25 mm glass	1250	930
24	30 mm glass	1020	670
25	25 mm glass	1490	1020
26	50 mm glass	1130	770

SECTION C

TABLE I-C

STABILITY TEST DATA

Pa   Pressure downstream side air nozzle in. Hg.
dHa   Pressure differential across air nozzle, in. water.
Ta   Temperature of air degrees Fahrenheit.
Pg   Pressure downstream side fuel nozzle, in. Hg.
dHg   Pressure differential across fuel nozzle, in. water.
T   Temperature in millivolts at center of combustion tube.

Run 1		
Tube 50 mm Bar 29.92 in. Hg.		
Pa	dHa	Ta
5.0	.50	67
Pg	dHg	T
5.4	.52	4.2
5.7	.62	7.5
5.8	.74	24.0
5.8	.77	30.0
6.1	.89	34.8
6.35	1.00	36.5
6.75	1.15	37.6
7.25	1.30	38.0
7.25	1.32	39.3
7.5	1.43	40.1
7.7	1.47	41.0

Run 2		
Tube 50 mm Bar 30.20 in. Hg.		
Pa	dHg	Ta
4.1	.50	66
Pg	dHg	T
5.2	.75	32.5
4.6	.56	15.8
4.6	.50	9.0
5.0	.66	23.0
5.2	.79	33.5
5.6	.92	35.5
5.9	1.04	36.2
6.1	1.16	37.8
6.2	1.24	38.2
6.4	1.26	38.0
6.7	1.40	39.2

Run 3		
Tube 50 mm Bar 29.92 in. Hg.		
Pa	dHa	Ta
6.5	.80	67
Pg	dHg	T
5.15	.87	3.5
9.7	1.15	15.5
10.3	1.35	32.0
10.8	1.55	37.0
11.0	1.78	40.5
11.4	1.97	41.8
11.7	2.14	42.0
12.5	2.47	43.6
12.6	2.52	43.6

Run 4		
Tube 50 mm Bar 30.20 in. Hg.		
Pa	dHa	Ta
7.8	.80	66
Pg	dHg	T
9.5	1.06	5.0
9.6	1.18	17.2
9.7	1.23	29.2
9.7	1.20	28.5
9.9	1.35	33.8
10.1	1.40	35.0
10.1	1.47	35.6
10.2	1.51	36.5
10.25	1.61	37.0
10.8	1.85	38.2
11.0	1.97	39.2
11.8	2.25	41.0
--	2.70	44.0

TABLE I-C (continued)

Run 5		
1 1/4" Pipe	Bar 29.92 in. Hg.	
Pg	dHa	Ta
4.1	.50	66
Pg	dHg	T
5.1	.50	4.5
5.7	.72	15.5
5.8	.96	37.1
6.35	1.14	40.0
7.0	1.33	41.2
7.2	1.43	42.5**
7.5	1.48	43.0
7.9	1.63	43.5
8.3	1.85	44.5
8.5	1.97	46.0
9.1	2.20	48.0
9.7	2.45	49.0

Run 6		
1 1/4" Pipe	Bar 29.92 in. Hg.	
Pa	dHa	Ta
4.1	.50	66
Pg	dHg	T
5.5	.70	11.8
5.7	.72	19.5
5.9	.80	33.0
6.3	1.00	38.8
6.5	1.20	40.9
7.1	1.43	42.5**

Run 7		
1 1/4" Pipe	Bar 29.92 in. Hg.	
Pa	dHa	Ta
8.5	.80	70
Pg	dHg	T
9.2	.75	8.5
10.1	1.26	22.5
10.8	1.50	38.8
10.9	1.57	39.0
10.35	1.37	33.0
11.25	1.77	41.0
11.4	1.99	42.3
12.3	2.22	43.5**

Run 8		
1" Pipe	Bar 29.92 in. Hg.	
Pa	dHa	Ta
5.1	.50	71
Pg	dHg	T
7.0	1.38	41.0
7.5	1.66	47.5
7.9	1.90	49.0
9.2	2.34	51.0
8.4	1.96	49.5
9.1	2.21	51.0**
10.1	2.61	52.0

Run 9		
1" Pipe	Bar 29.92 in. Hg.	
Pa	dHa	Ta
5.8	.70	72
Pg	dHg	T
9.0	1.86	42.0
9.9	2.14	49.2
10.3	2.49	50.5
11.3	2.88	52.0**

Run 10		
1" Pipe	Bar 30.20 in. Hg.	
Pa	dHa	Ta
4.8	.50	66
Pg	dHg	T
7.8	1.63	44.5
8.2	1.77	47.3
8.6	2.01	48.8
9.3	2.20	49.5
9.9	2.36	50.0**
10.4	2.67	51.2
10.8	2.82	51.5
10.0	2.50	50.5

**Point where first audible continuous pulsation observed.

TABLE I-C (continued)

Run 11		
1" Pipe	Bar 30.20 in. Hg.	
Pa	dHa	Ta
4.8	.50	66
Pg	dHg	T
8.2	1.63	41.0
8.3	1.76	44.0
8.4	1.80	45.5
8.9	1.98	48.2
9.4	2.24	49.5
10.1	2.50	50.5**
11.1	2.95	53.0

Run 12		
1 1/4" Pipe	Bar 30.20 in. Hg.	
Pa	dHa	Ta
4.6	.50	69
Pg	dHg	T
5.6	.72	16.5
5.6	.73	19.5
5.9	.90	33.5
6.2	1.03	36.7
6.6	1.23	38.9
6.9	1.34	40.0
7.4	1.50	41.2**
7.7	1.69	42.1
8.0	1.84	43.1
8.4	2.00	44.7
9.2	2.36	45.7
10.1	2.67	47.0

Run 13		
1 1/4" Pipe	Bar 30.35 in Hg.	
Pa	dHa	Ta
4.9	.50	68
Pg	dHg	T
5.8	.56	10.5
6.0	.68	20.5
6.1	.74	31.2
6.1	.76	35.5
6.8	.94	38.2
7.2	1.07	39.0
7.8	1.30	41.2
8.8	1.60	43.0**
9.2	1.74	44.0
10.9	2.30	47.0

Run 14		
1 1/4" Pipe	Bar 30.35 in. Hg.	
Pa	dHa	Ta
4.9	.50	68
Pg	dHg	T
6.1	.63	21.0
6.5	.75	33.6
6.8	.90	37.2
7.2	1.00	38.6
7.4	1.22	40.8
8.0	1.36	41.8
8.6	1.53	42.8**
9.0	1.76	44.5
10.0	2.05	45.5
10.9	2.25	46.5

**Point where first audible continuous pulsation observed.

TABLE I-C (continued)

Run 15		
1 1/4" Pipe Bar 30.35 in. Hg.		
Pa	dHg	Ta
9.0	.80	68
11.1	1.33	36.2
10.6	1.16	31.2
12.0	1.55	39.0
12.3	1.67	39.8
12.6	1.82	41.2
13.2	2.05	42.2**
14.0	2.25	43.2
14.6	2.42	44.0
15.2	2.63	45.2
16.2	2.98	46.2

Run 16		
1 1/4" Pipe Bar 30.35 in. Hg.		
Pa	dHg	Ta
9.0	.80	68
11.0	1.25	33.4
11.4	1.40	38.2
11.6	1.55	39.5
12.0	1.65	40.1
12.7	1.78	41.1
13.2	2.07	43.0**
13.6	2.20	43.2
14.4	2.38	44.1
14.8	2.54	44.8
15.2	2.66	45.2
15.8	2.85	46.1
16.4	3.03	46.2

Run 17		
1" Pipe Bar 30.35. in. Hg.		
Pa	dHg	Ta
5.0	.50	68
Pg	dHg	T
8.2	1.82.	42.0
8.2	1.86	43.1
8.9	1.96	44.5
9.3	2.14	45.5
10.0	2.37	46.5
10.25	2.56	47.5
--	2.60	47.2
11.2	2.96	49.5

Run 18		
1" Pipe Bar 30.35 in. Hg.		
Pa	dHa	Ta
5.0	.50	70
Pg	dHg	T
9.1	1.69	43.8
9.5	1.79	44.6
10.0	1.92	45.8
10.5	2.07	46.8
11.3	2.28	47.5
12.2	2.57	49.5
13.2	2.84	51.0

**Point where first audible continuous pulsation observed.

TABLE I-C (continued)

Run 19		
35 mm Tube Bar 30.35 in Hg.		
Pa	dHg	Ta
4.8	.50	70
Pg	dHg	T
6.2	.81	23.1
6.7	.92	36.1
6.8	.96	37.8
7.0	1.12	39.2
7.2	1.20	40.0
7.4	1.30	41.0
8.0	1.50	42.1
7.8	1.35	41.0
8.7	1.75	44.0
9.0	1.89	44.5
9.5	2.08	44.0
10.9	2.55	46.0**

Run 20		
Tube 35 mm Bar 30.35 in. Hg.		
Pa	dHa	Ta
4.8	.50	70
Pg	dHg	T
6.0	.70	26.5
6.2	.78	30.3
6.4	.86	35.2
6.5	.97	37.5
6.8	1.07	38.8
7.2	1.20	40.2
7.5	1.24	40.5
7.8	1.33	41.2
8.0	1.57	42.3
8.5	1.67	43.3
8.9	1.83	44.5
9.2	1.95	45.5
9.9	2.17	46.0**
10.3	2.36	46.2
11.0	2.55	47.0

Run 21		
35 mm Tube Bar 30.35 in. Hg.		
Pa	dHa	Ta
8.1	.80	70
Pg	dHg	T
10.6	1.33	28.5
11.3	1.56	38.7
11.8	1.66	40.0
12.3	1.92	41.5
12.6	2.03	42.6
13.0	2.15	42.8
13.2	2.24	43.0
14.0	2.43	44.0
14.2	2.66	45.1
15.0	2.88	46.0**
17.8	3.00	45.0

Run 22		
Tube 35 mm Bar 30.35 in. Hg.		
Pa	dHa	Ta
8.1	.80	70
Pg	dHg	T
10.6	1.26	29.5
11.0	1.42	36.0
11.4	1.64	39.2
11.9	1.77	40.5
12.3	1.98	42.0
12.7	2.09	42.1
12.7	2.24	43.0
14.2	2.60	45.0
14.7	2.78	45.5
15.2	2.92	46.2**

**Point where first audible continuous pulsation observed.

TABLE II-C

RESULTS OF STABILITY TESTS

Tc' Lower limit of stability temperature in millivolts at
     center of combustion tube.
Tc" Temperature in °F. corresponding to Tc'.
To   Average temperature obtained from Curve 3.
To/Ta Temperature ratio.
Tp   Temperature in millivolts corresponding to first
     sustained audible pulsation.

Run	Tube	Tc'	Tc"	To	To/Ta	Tp
1	50 mm	33.5	1480	1030	2.82	--
2	50 mm	34.5	1525	1075	2.89	--
3	50 mm	35.0	1545	1090	2.94	--
4	50 mm	35.0	1545	1090	2.94	--
5	1 1/4"pipe	37.7	1670	1230	3.20	42.5
6	1 1/4"pipe	37.5	1660	1215	3.17	42.5
7	1 1/4"pipe	38.0	1680	1245	3.23	43.5
8	1" pipe	47.0	2100	1785	4.26	51.0
9	1" pipe	48.0	2150	1850	4.38	52.0
10	1" pipe	47.2	2110	1800	4.28	50.0
11	1" pipe	47.2	2110	1800	4.28	50.5
12	1 1/4"pipe	37.0	1635	1190	3.12	41.2
13	1 1/4"pipe	36.7	1622	1185	3.11	43.0
14	1 1/4"pipe	36.7	1622	1185	3.11	42.8
15	1 1/4"pipe	38.0	1680	1240	3.22	42.2
16	1 1/4"pipe	38.2	1690	1255	3.24	43.0
17	1" pipe	45.5	2055	1695	4.06	--
18	1" pipe	45.5	2055	1695	4.06	--
19	35 mm	39.5	1750	1325	3.38	46.0
20	35 mm	39.4	1745	1320	3.37	46.0
21	35 mm	39.7	1760	1335	3.39	46.0
22	35 mm	39.5	1750	1325	3.38	46.2

MEAN RESULTS

	To/Ta(Lower Limit)	Tp/Ta(Pulsation)
Tube No. 1; 50 mm	2.88	--
Tube No. 2; 1 1/4"pipe	3.19	3.75
Tube No. 3; 35 mm	3.39	4.15
Tube No. 4, 1" pipe	4.20	4.73

TABLE III-C

AIR TO FUEL RATIO FOR STABILITY TESTS

Run	Lower Limit-Air to Fuel Ratio	Audible Pulsation-Air To Fuel Ratio
1	27.7	--
2	28.1	--
3	26.5	--
4	27.0	--
5	26.2	20.1
6	26.7	20.1
7	26.0	20.6
8	20.1	16.2
9	20.5	16.4
10	18.4	15.6
11	18.15	15.0
12	25.8	19.9
13	28.0	--
14	27.8	18.7
15	26.1	21.3
16	26.1	21.2
17	17.45	--
18	17.5	--
19	25.4	14.7
20	25.4	16.1
21	24.5	18.0
22	25.1	17.3

MEAN VALUES OF AIR TO FUEL RATIO

Tube No. 1	27.3	--
Tube No. 2	26.6	20.3
Tube No. 3	25.1	16.5
Tube No. 4	18.7	15.8

**Stoichiometric composition for combustion of propane
corresponds to an air to fuel ratio of 15.8.

SECTION D

AIR AND FUEL FLOW CALCULATIONS

Air Measurement:

γ Ratio of specific heats, 1.395 for air.

k Slope of the f(M) flow curve for very low Mach Numbers, .918.

A Air nozzle area, .187 sq. in.

Pa Pressure at downstream side of air nozzle in in. Hg.

dHa Differential pressure across the air nozzle in in. water.

$$\frac{Po}{Pa} = \left[1 + \frac{\gamma-1}{2} M^2 \right]^{\frac{\gamma}{\gamma-1}} = 1 + \frac{\gamma M^2}{2} \cdots$$

$$\frac{Po - Pa}{Pa} = \frac{dHa}{Pa} = \frac{\gamma M^2}{2} \quad \text{for low Mach Numbers } M < .1$$

$$Ma = \sqrt{\frac{2}{\gamma} \frac{dHa}{Pa}}$$

$$\frac{W\sqrt{To}}{PA} = M\sqrt{\frac{\gamma g}{R} \left(1 + \frac{\gamma-1}{2} M^2\right)} = K(M) \quad \text{for low Mach Numbers}$$

$$W = .491 \times .918 \times .187 \sqrt{\frac{2}{r} \frac{1}{13.6}} \sqrt{\frac{Pa \, dHa}{Ta}}$$

$$W = .0274 \sqrt{\frac{Pa \, dHa}{Ta}} \quad \text{lb. air/sec.}$$

Fuel Measurement:

r Ratio of specific heats of propane, 1.153

k Slope of the f(M) flow curve for very low Mach numbers for propane, 1.0295.

A Area of the fuel nozzle by calibration, .00425 sq. in.

Pg   Pressure on the downstream side of the fuel
     nozzle in in. Hg.

dHg Differential across the fuel nozzle in in. water.
     Using the binominal expansion for low Mach Numbers
     as in air measurement.

$$Mg = \sqrt{\frac{2}{r}\frac{dHg}{Pg}} = \sqrt{\frac{2}{r}\frac{1}{13.6}\frac{dHg}{Pg}} = .355\sqrt{\frac{dHg}{Pg}}$$

but,

$$\frac{w\sqrt{To}}{PA} = M\sqrt{\frac{rg}{R}\left(1+\frac{r-1}{2}M^2\right)} = KMg = 1.0295\ Mg$$

$$w = .491 \times 1.0295 \times .355 \times .00425\sqrt{\frac{Pg\ dHg}{Tg}} =$$

$$.000764\sqrt{\frac{Pg\ dHg}{Tg}}\ \text{lb./sec. propane}$$

SECTION E

ORSAT ANALYSIS

DATA:

Pa	5.1 in Hg. Gage	Pg	6.5 in Hg. gage
dHa	.51 in H_2O	dHg	.95 in H_2O
ta	66° F.	To	36 millivolts
Combustion tube 1 1/4" pipe		Bar	29.77 in Hg.

Orsat Analysis Results:

	Run 1	Run 2	Average
CO_2	6.8%	7.5%	7.15%
O_2	9.0%	9.8%	9.4%
CO	Neg.	Neg.	Neg.
N_2	84.2%	82.7%	83.45%

Calculations:

Basis 100 moles of dry gas.

Carbon = 7.15 x 44 x 12/44 = 85.6 lbs.

Weight Propane = 85.6 x 44/36 = 105 lbs. propane for
100 moles dry gases.

Weight Air = 83.45 x 28/77 = 3030 lbs. air for 100
moles dry gases.

Air/Fuel Ratio from Orsat = 3030/105 = 28.8

Air/Fuel Ratio, Run 2 = 27.3

From Air and Fuel Meters:

Weight Air = .0274 $\sqrt{\dfrac{Pa\ dHa}{Ta}}$ = .00502 lbs. air/sec.

Weight Fuel = .000764 $\sqrt{\dfrac{Pg\ dHg}{Tg}}$ = .000195 lbs. fuel/sec.

Air/Fuel Ratio from Meters = .00502/.000195 = 25.8

Calculations of Carbon to Hydrogen Ratio:

Weight of Carbon = 85.6 lbs.

Weight of O_2 = 3030 x .23 = 696 lbs.

Weight of O_2 Excess = 9.4 x 32 = 301 lbs.

Weight of O_2 in CO_2 = 7.15 x 32 = 229 lbs.

wt O_2 in H_2O = 696 - (301+299) = 166 lbs.

wt. of H. in fuel = 166 x 2/16 = 20.7

C/H ratio observed = $\dfrac{\dfrac{85.6}{12}}{20.7/1}$ = $\dfrac{7.14}{20.7}$ = $\dfrac{2.76}{8}$

C/H ratio of fuel, propane = 3/8

SECTION F

SYMBOLS

A = Flow area, sq. ft.

dH = Differential drop across meter in in. of water.

g = Acceleration of gravity, 32.2 ft. per sec. per sec.

M = Mach number.

P = Absolute pressure, lbs. per sq. ft.

γ = Ratio of specific heats.

R = Gas constant, 53.3 in. lbs. ft. per ^{o}R.

T = Static temperatures ^{o}R.

To = Total temperature ^{o}R.

V = Velocity, ft. per second.

W = Flow, lbs. per second.

ρ = Mass density slugs per cu. ft.

d = Total derivative

δ = Partial derivative

Subscripts are used throughout paper for designation of
point properties, and where they are used their significance
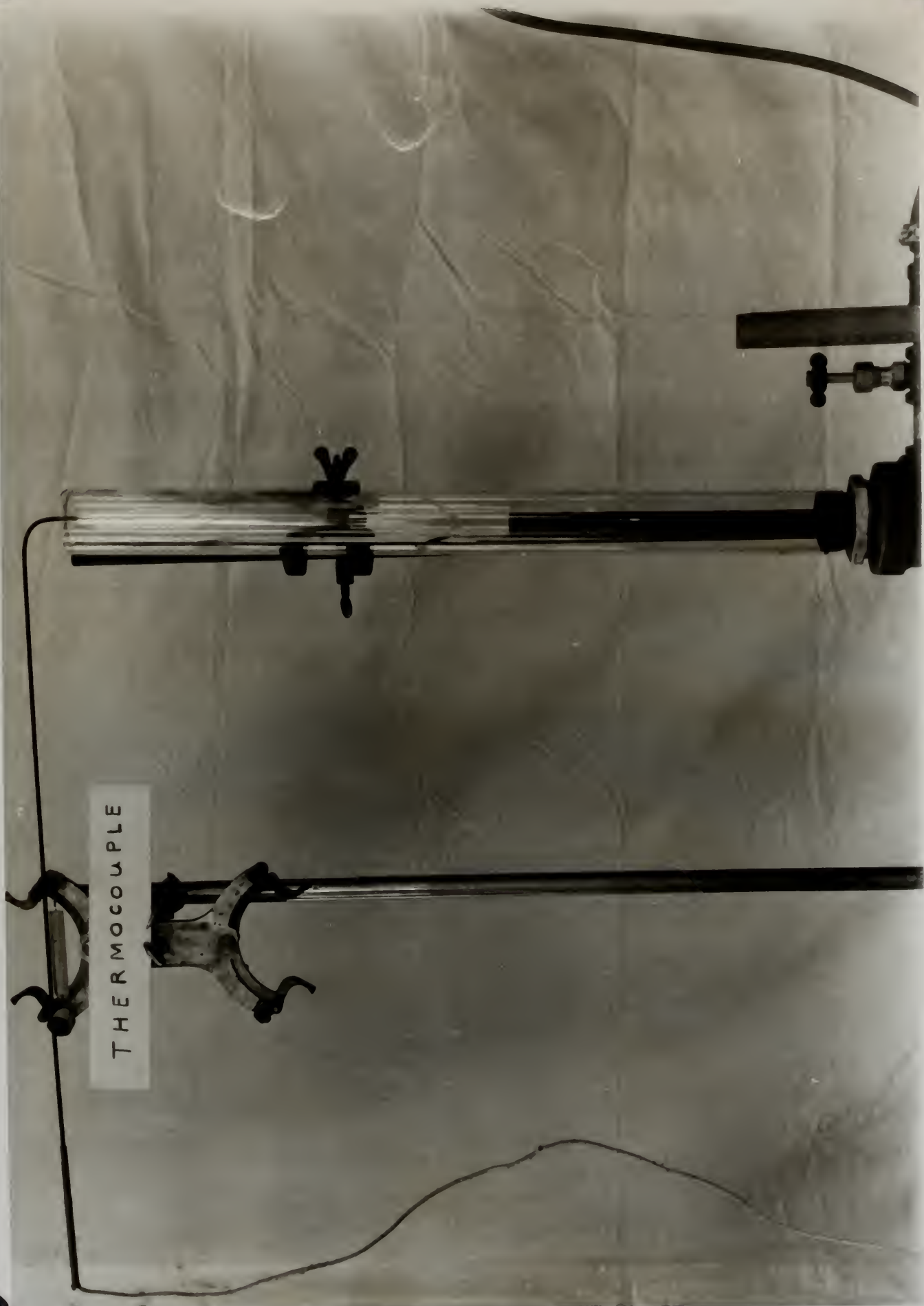is explained.

SECTION G

PHOTOGRAPHS

Photograph 1 – The experimental apparatus.

Photograph 2 – Details of combustion tube.
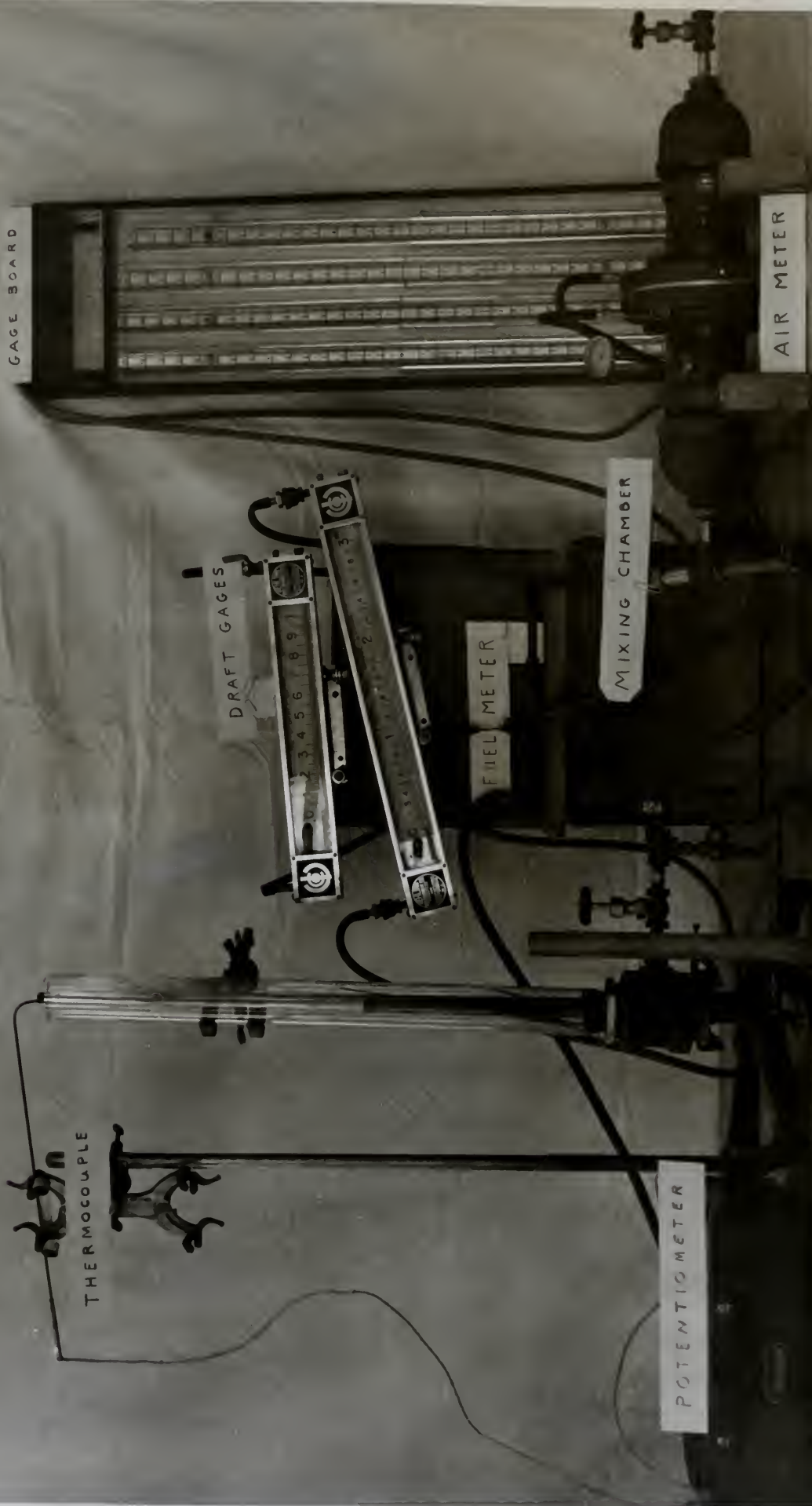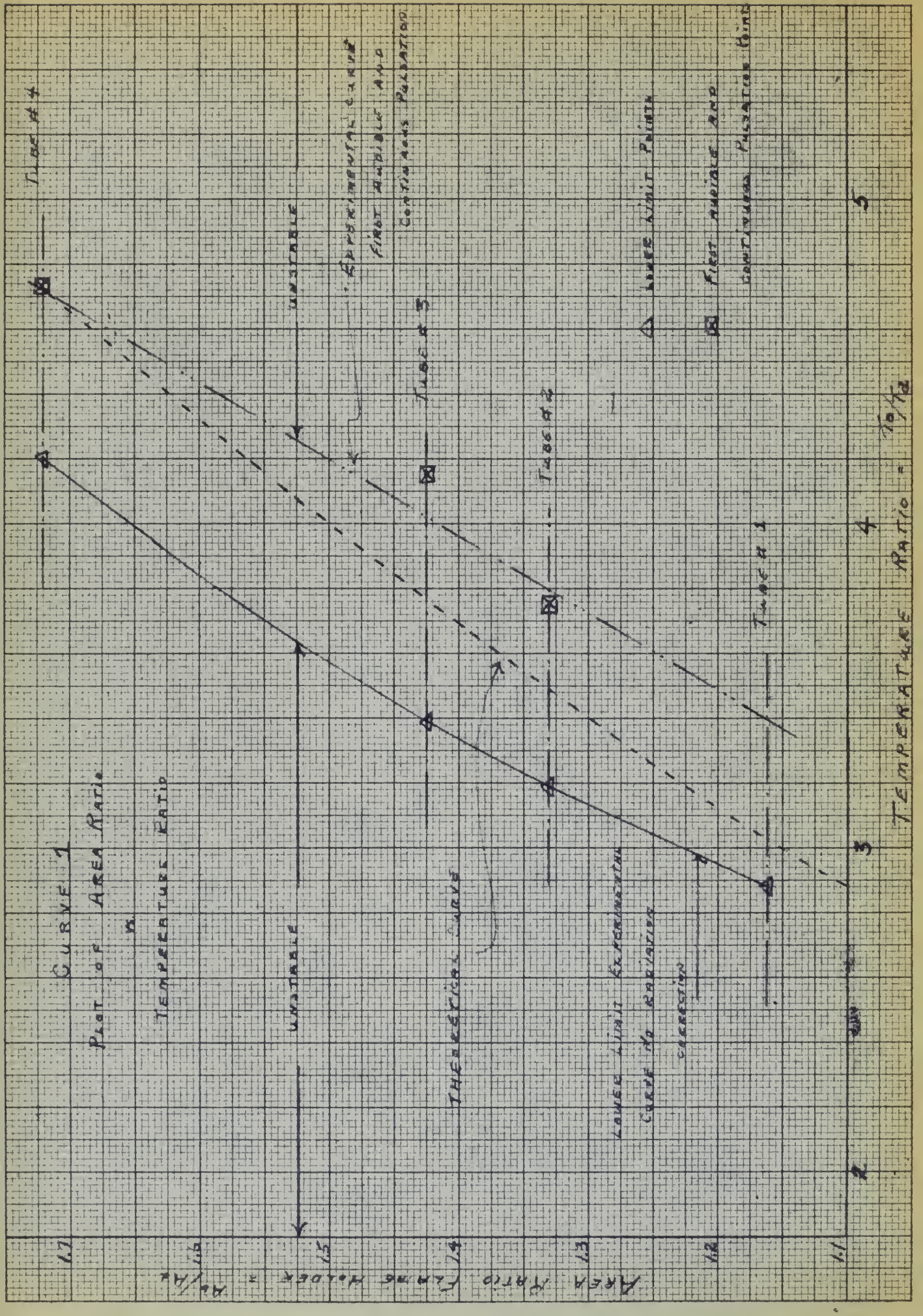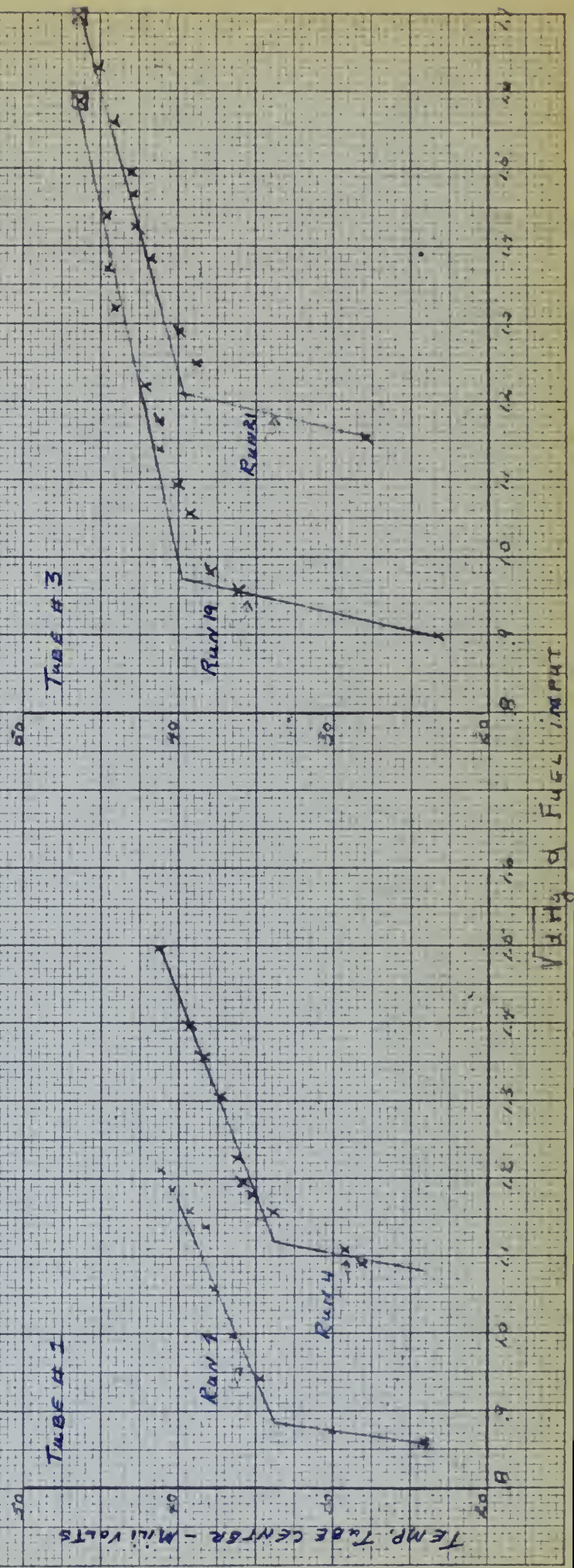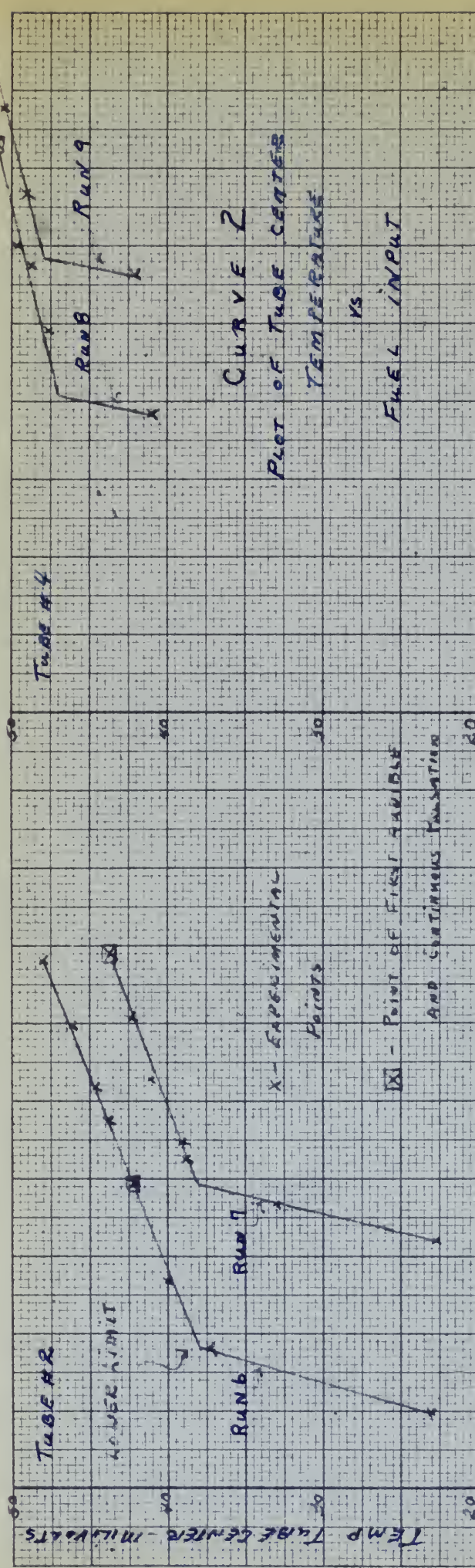
PHOTOGRAPH 1 - THE EXPERIMENTAL APPARATUS

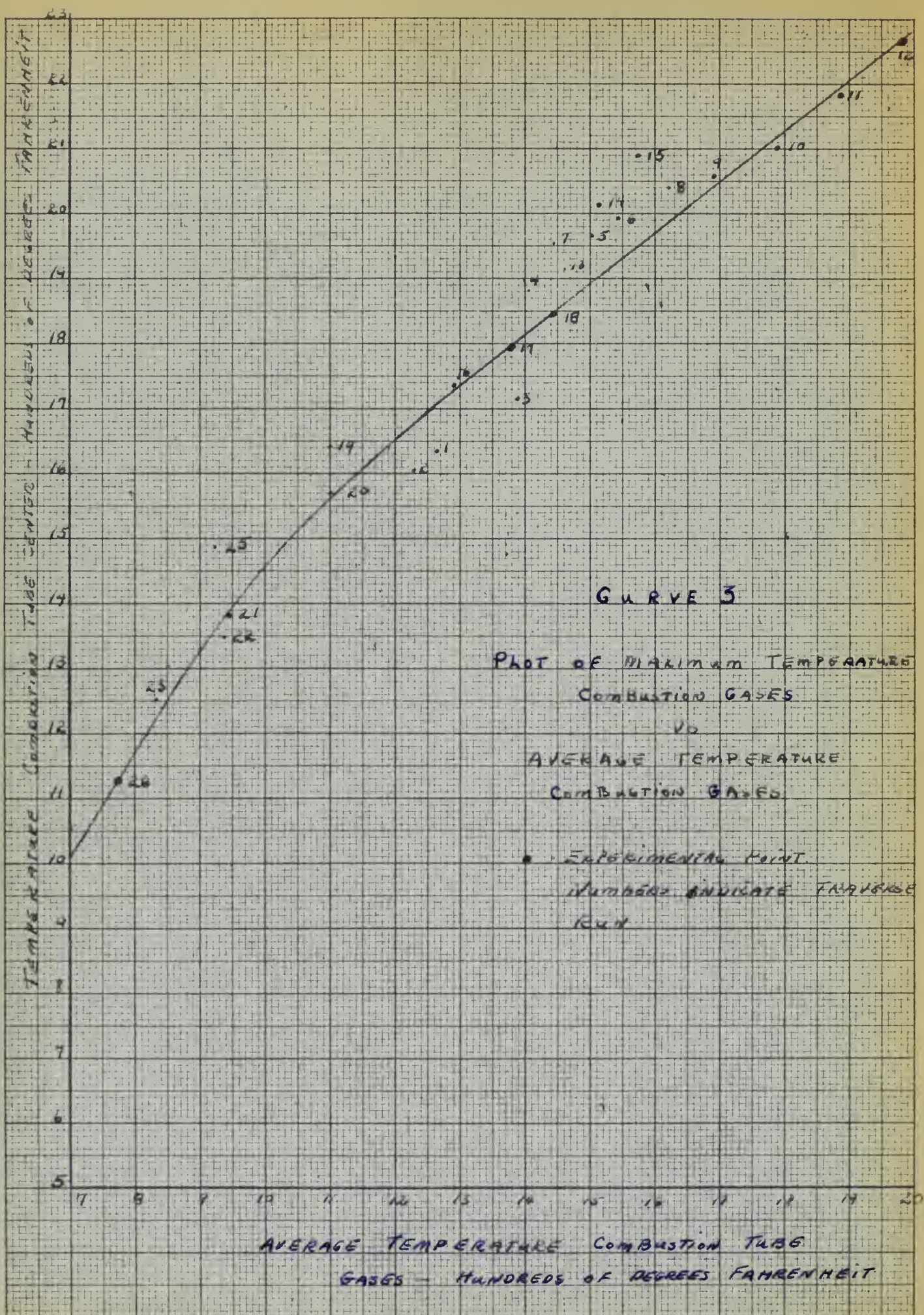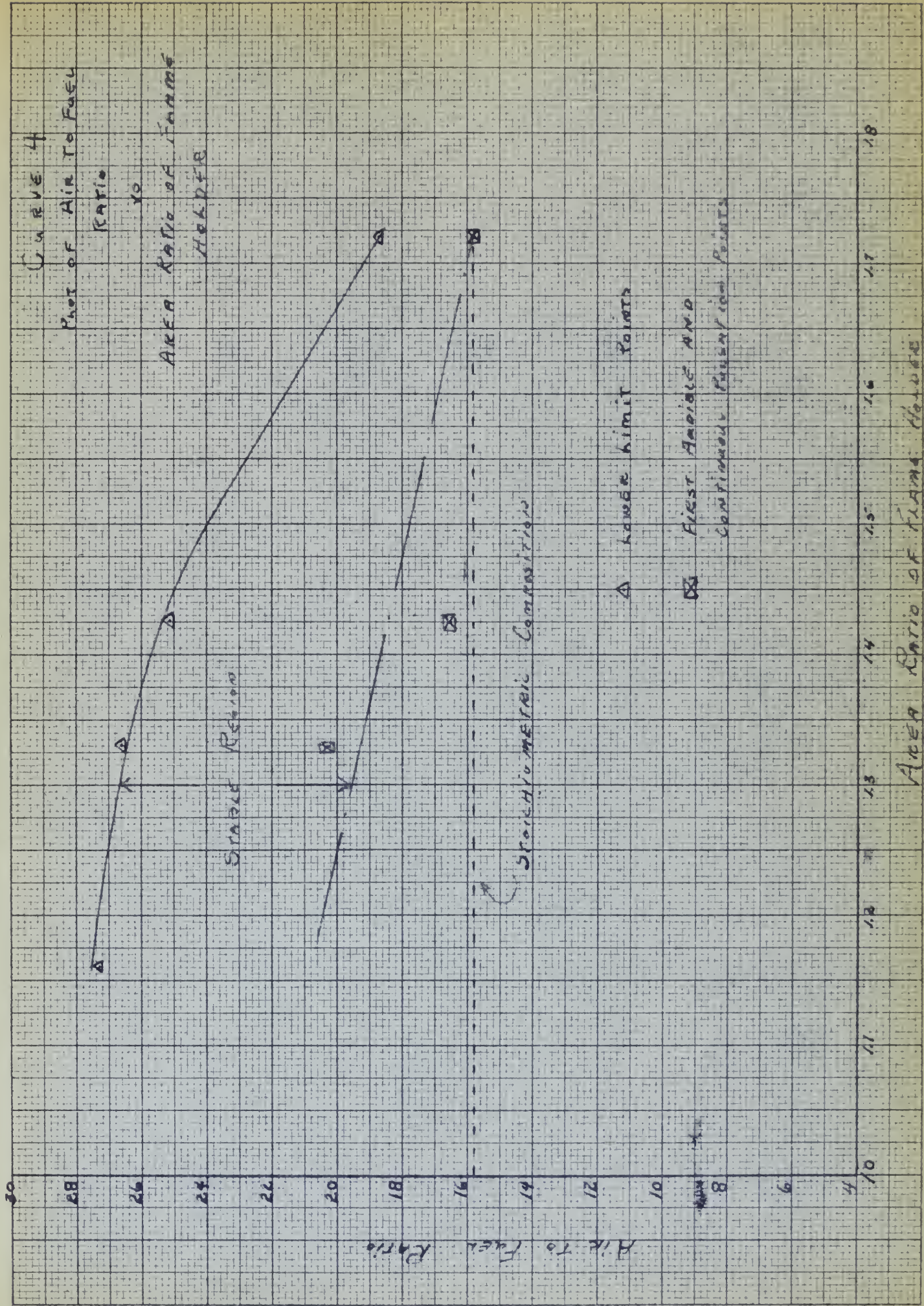PHOTOGRAPH 2 - DETAILS OF THE COMBUSTION TUBE

SECTION H

CURVES

Curve 1 - Plot of area ratio versus temperature ratio.

Curve 2 - Plot of tube center temperature versus fuel input.

Curve 3 - Plot of maximum temperature of combustion gases
versus average temperature of combustion gases.

Curve 4 - Plot of air to fuel ratio versus area ratio of
flame holder.

CURVE 1

Plot of Area Ratio
vs.
Temperature Ratio

Theoretical Curve

Lower Limit Experimental
Curve No Radiation
Correction

△ Lower Limit Points
⊠ First Audible And
Continuous Pulsations (time)

"Experimental Curve"
First Audible And
Continuous Pulsation

Tube # 4
Tube # 5
Tube # 2
Tube # 3

UNSTABLE

UNSTABLE

Area Ratio Flame Holder = A_E/A_A

1.7
1.6
1.5
1.4
1.3
1.2
1.1

Temperature Ratio = T_0/T_A

2   3   4   5

Curve 2

Plot of Tube Center
Temperature
vs
Fuel Input

X — Experimental
Points

☒ — Point of First Audible
and Continuous Pulsation

Temp. Tube Center — Millivolts

V·d·H₂·d Fuel Input.

CURVE 3

PLOT OF MAXIMUM TEMPERATURE
COMBUSTION GASES
VS
AVERAGE TEMPERATURE
COMBUSTION GASES

• EXPERIMENTAL POINT
NUMBERS INDICATE TRAVERSE
RUN

AVERAGE TEMPERATURE COMBUSTION TUBE
GASES — HUNDREDS OF DEGREES FAHRENHEIT

Curve 4

Plot of Air to Fuel Ratio
to
Area Ratio of Flame Holder

Stable Region

Stoichiometric Composition

Range Limit Points

First Misfire and
Continuous Physical Points

Air To Fuel Ratio

Area Ratio of Flame Holder

SECTION I

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